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DSTO-TN-0197

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ABSTRACT

As Vertical Line Arrays (VLA) are used at increasingly higher frequencies (3 kHz), the importance of the straightness of the array increases. Finite Element Analysis (FEA) has been used to estimate the shape of typical VLAs subject to currents in shallow water. Two typical VLA configurations have been modelled and the results presented.

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Executive Summary

Vertical Line Acoustic Arrays (VLA) are being used at increasingly higher frequencies (3 kHz). At these frequencies, the alignment of the hydrophones in the array relative to each other (straightness) is of great importance. One method of straightening the array is to increase the tension applied to it. Finite Element Analysis (FEA) has been used to estimate the straightness of two typical VLAs subject to current flow in shallow waters.

The analysis shows that the position of the array can be described as a horizontal displacement of a reference point, a rotation or tilt about that point and the deviation of the hydrophones from the mean line through the hydrophone positions. In terms of beamforming, displacement should cause no error except in the very near field; rotation causes some error and deviation the greatest error.

FEA demonstrates that adding tension to the VLA decreases displacement, rotation and deviation. However, there is a practical limit to the reduction obtainable as each variable asymptotes rapidly towards a constant value as the tension is increased. Adding tension to the VLA is most efficient at reducing displacement and least efficient at reducing deviation.

The conclusion of the analysis is that applying tension to a VLA is not an effective or practical method of reducing the rotation and deviation of the array when beamforming at frequencies in the 3 kHz band.

Authors

Michael H. Davis
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Michael Davis completed a Bachelor of Science Degree with Honours in Aeronautical Engineering at City University, London, in 1962. He worked for two years as an aircraft systems engineer at the de Havilland Division of Hawker Siddeley Aviation. After emigrating to Australia, he spent several years in air conditioner design, research and development. He joined DSTO in 1980 and started work on towed array sonar systems in 1985.

Contents

1. Introduction

As Vertical Line Arrays (VLA) are used at increasingly higher frequencies (3 kHz), the importance of the straightness of the array increases. Finite Element Analysis (FEA) has been used to estimate the shapes of typical VLAs subject to currents in shallow water. Two typical arrays, one bottom moored the other surface moored, have been modelled and the results presented.

2. The Models

The computer models, illustrated in Figure 2.1, were generated and analysed using the ANSYS® finite element analysis software [1] run on a Unix workstation. Sample model and solution input files for the Bottom Moored Array are presented in Appendix A and the Surface Moored Array in Appendix B. The models are highly non-linear and both stress stiffening and large deflection effects have to be included. All external components were modelled using the PIPE59, 'immersed pipe or cable' element. This is the only element that can include the effects of external loads, inertia, buoyancy and hydrodynamic forces. The tube of an array is usually filled with an 'incompressible' fluid and pressurised to approximately 1 to 2 atmospheres. As this element cannot model a contained, incompressible fluid, an increased internal pressure of 4 atmospheres was applied to the tube to avoid 'tube collapse' error messages that frequently occur during the solution sequence. All external elements were assigned a Reynolds Number independent, normal drag coefficient of 1.2. Internal braided cord strength members were modelled using the non-linear LINK10, 'tension only spar' element. The models were considered to be moored in 40 m depth of sea water with a density of 1025 kg/m³.

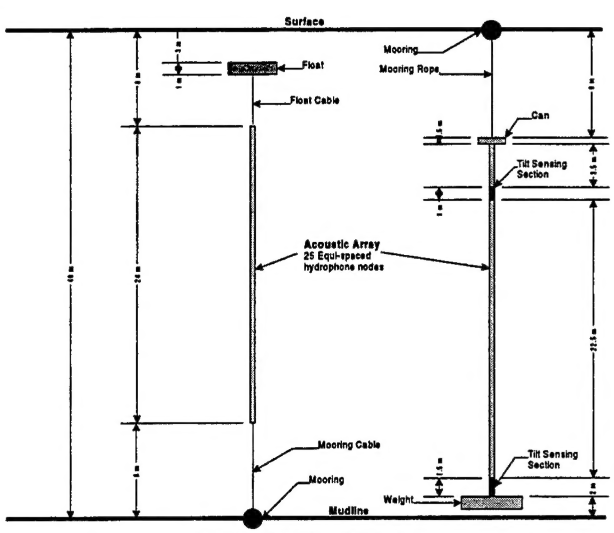

Figure 2.1 Schematic of Models

2.1 Bottom Moored Array

The first VLA modelled was bottom moored and comprised a float, float cable, array and mooring cable fixed at the mudline. The complete VLA has a mass of 162.3 kg in air and has a negative buoyancy force of 15.9 N in seawater. The mechanical and physical properties of the VLA are shown in Table 2-1 and Table 2-2.

Table 2-1 Mechanical Properties - Bottom Moored Array

	Modulus of Elasticity [Pa]	Density [kg/m³]	Poisson's Ratio	Internal Components [kg/m]
Float	68.26×10^9	1025	0.33	
Float Cable	20.0×10^9	763	0.29	
Strength Member	20.0×10^9	1067	0.33	
Array Tube	18.4×10^6	1320	0.33	0.8186
Mooring Cable	53.3×10^9	5385	0.29	

Table 2-2 Physical properties - Bottom Moored Array

	Length m	Diameter [mm]	Wall Thickness [mm]	Cross Sectional Area [m²]	Element Length [m]	Number of Elements	Crossflow Drag Coefficient
Float	1	400			1	1	1.2
Float Cable	4	12.7			1	4	1.2
Strength member #1	24			4.28×10^{-6}		24	
Strength member #2	24			4.28×10^{-6}		24	
Array Tube	24	40	3			24	1.2
Mooring Cable	8	8			1	8	1.2

2.1.1 Float

To enable the tension in the array to be easily changed, the float was modelled as a rigid cylinder of neutral buoyancy, and a vertical, upward force was applied at the top of the float to simulate its buoyancy force.

2.1.2 Float Cable

The float cable was modelled as a polypropylene rope.

2.1.3 Acoustic Array

The acoustic array comprised an outer cylindrical, hollow tube, modelled using the cable formulation (no bending stiffness), containing two chord-like strength members. The strength members were constrained in position in the tube at 1 m intervals as illustrated in Figure 2.2. The mass of the internal components and fluid fill was set to make the array neutrally buoyant.

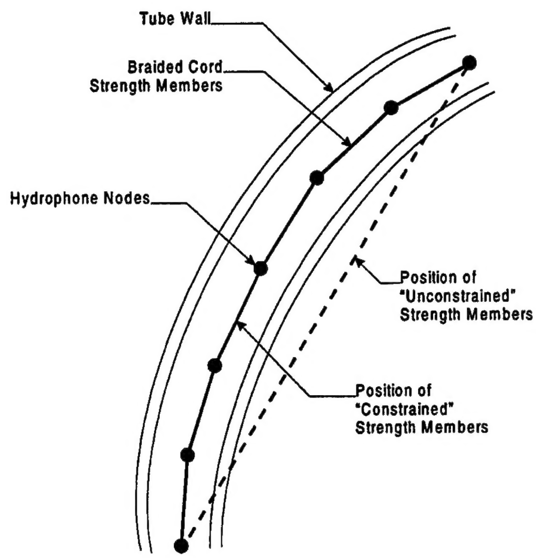

Figure 2.2 Schematic of Array Model

2.1.4 Mooring Cable

The mooring cable was modelled as a stranded steel cable. It was anchored at the bottom.

2.2 Surface Moored Array

The second VLA modelled was surface moored and comprised a mooring rope, electronics can, array and a weight. The complete VLA has a mass of 259 kg in air and has a positive buoyancy force of 2.9 N in sea water. The mechanical and physical properties of the VLA are shown in Table 2-3 and Table 2-4.

2.2.1 Mooring Rope

The mooring rope was modelled as a polypropylene rope. It was anchored at the surface.

2.2.2 Electronics Can

The electronics can was modelled as a rigid cylinder of neutral buoyancy.

2.2.3 Acoustic Array

The acoustic array comprised an outer cylindrical, hollow tube containing two strength members, fluid fill and internal components. The strength members were constrained in position in the tube at approximately 1 m intervals. The mass of the internal components and fluid fill was set to make the array neutrally buoyant.

Table 2-3 Mechanical Properties Surface Moored Array

	Modulus [Pa]	Density [kg/m³]	Poisson's Ratio	Internal Components [kg/m]
Mooring Rope	20.0×10^{9}	763	0.29	
Electronics Can	68.3×10^{9}	1025	0.33	
Strength Member	20.0×10^{9}	1067	0.33	
Array Tube	18.4×10^{6}	1320	0.33	0.8186
Weight	68.3×10^{9}	1025	0.33	

Table 2-4 Physical Properties - Surface Moored Array

	Length m	Diameter [mm]	Wall Thickness [mm]	Cross Sectional Area [m²]	Element Length [m]	Number of Elements	Crossflow Drag Coefficient
Mooring Rope	9	12.7			1	9	1.2
Electronics Can	0.5	220			0.5	1	1.2
Strength member #1	28.5			4.28×10^{-6}		31	
Strength member #2	28.5			4.28×10^{-6}		31	
Array Tube	28.5	40	3			31	1.2
Weight	1.0	500			1	1	1.2

2.2.4 Weight

To enable the tension in the array to be easily changed, the weight was modelled as a rigid cylinder of neutral buoyancy, and a vertical, downward force was applied at the bottom of the weight to simulate its inertia (gravitational) force.

3. Loads

3.1 Inertia Forces

Both models were loaded by inertia forces generated by the software from the masses and acceleration due to gravity (9.81 m/s²) acting vertically down.

3.2 Buoyancy Forces

The software generated the appropriate buoyancy forces to be applied to each model using the geometric and density data.

3.3 Hydrodynamic Forces

Both models had hydrodynamic forces generated by the software using the geometry, drag coefficients and the current velocity. Two current profiles were used.

3.3.1 Constant Current

The applied current was considered constant throughout the water depth at 0.6 knots (0.31 m/s).

3.3.2 Profiled Current

The applied current was shaped with water depth as shown in Figure 3.1.

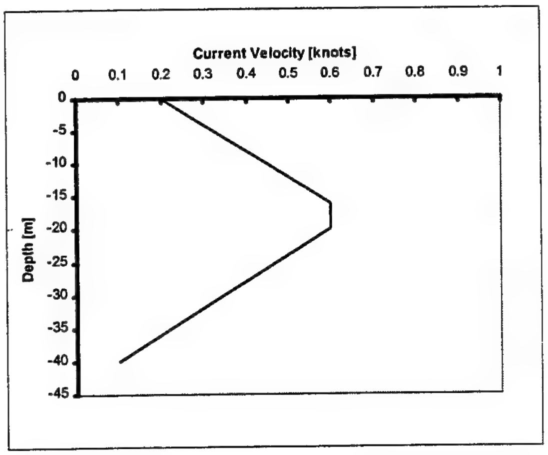

Figure 3.1 Shaped Current profile

3.4 Applied Tension

An applied force tensioned the VLA. This force was varied to illustrate the variation of the straightness of the array with the applied tension. The force ranged from 100 N to 1000 N in steps of 100 N in most runs.

3.4.1 Bottom Moored Array

The force was applied vertically upward at the top of the float. This simulated a float with fixed geometry, hence constant drag forces, and variable buoyancy.

3.4.2 Surface Moored Array

The force was applied vertically downward at the bottom of the weight. This simulated a weight with fixed geometry, hence constant drag forces, and variable mass.

4. Results

The FEA models were run using ANSYS finite element analysis program. Results were either plotted directly in ANSYS or transferred to EXCEL for further analysis and plotting. Table 4-1 summarises the parameters used in each analysis.

Table 4-1 Summary of Analyses

Analysis Folder	Model File	Solution File(s)	Tension Range [N]		Sea State	Current Range [knots]			Comment
			Min.	Max.		Min	Max	Profile	
a	spread1	sol01+02		1000	0		0.6	Constant	Deleted
b	spread1	sol03	20	1000	0		0.6	Constant	Deleted
c	spread1	sol03	100	1000	0		0.6	Constant	Deleted
d	spread1	sol04	100	1000	0		0.6	Constant	Bottom Moored
e	spread1	sol05	100	1000	0		0.6	Shaped	
f	spread1a	sol04	100	1000	0		0.6	Constant	1 Strength Member
g	spread1	sol06	100	1000	3		0.6	Constant	Deleted
h	spread1	sol09	100	1000	3		0.6	Constant	
i	spread1	sol07		500	0	0.1	1.0	Constant	
a	spread2	solution.01	100	1000	0		0.6	Constant	Surface Moored

4.1 Summary of Results

The deflection of the acoustic array can be considered as having three components:

a) a lateral displacement of a reference point, the node representing the hydrophone nearest the mooring, on the acoustic array
b) a rotation about the reference point of the mean line through the acoustic array from the vertical and
c) a horizontal deviation of the nodes representing the hydrophones from the mean line.

Folders d, e and f were analysed to determine the mean line through the nodes in the acoustic array at 1000, 500 and 100 N. The mean line was obtained by a linear 'least squares fit' through the deflected position of the nodes. The rotation of this mean line to the vertical and the horizontal deviation of the nodes from this line were calculated The total deviation is the sum of the maximum positive and negative deviations obtained. The results are summarised in Table 4-2 and Table 4-3.

Examination of these tables shows that the maximum rotation and deviation occurs with a constant current profile. The shaped current profile causes lower hydrodynamic loads due to the decreased mass flow past the VLA, although the maximum current speed was the same in both instances.

Table 4-2 Results Summary - Bottom Moored Array

Run	Sea State	Maximum Current		Tension	Rotation	Maximum Deviation		
		Speed [knots]	Type	[N]	[degrees]	-ve [m]	+ve [m]	Total [m]
spread1d	0	0.6	Constant	1000	3.2	-0.121	0.061	0.182
				500	6.1	-0.231	0.117	0.348
				100	19.4	-0.772	0.393	1.165
spread1e	0	0.6	Shaped	1000	1.7	-0.106	0.053	0.159
				500	3.2	-0.206	0.102	0.308
				100	11.8	-0.766	0.372	1.138
spread1f	0	0.6	Constant	1000	3.2	-0.121	0.061	0.182
				500	6.0	-0.231	0.117	0.348
				100	19.4	-0.768	0.391	1.159

Table 4-3 Results Summary - Surface Moored Array

Run	Sea State	Maximum Current		Tension	Rotation	Maximum Deviation		
		Speed [knots]	Type	[N]	[degrees]	-ve [m]	+ve [m]	Total [m]
spread2a	0	0.6	Constant	1000	3.4	-0.105	0.054	0.159
				500	6.5	-0.199	0.102	0.301
				100	19.8	-0.622	0.322	0.944

These tables also show that although the angle of rotation is greater for the surface moored array than for the bottom moored one the deviations are less for the former mooring position. The differences in the deviations are quite small and are probably caused by the geometry changes between the two systems.

4.2 Comparison of Bottom and Surfaced Moored Arrays

To compare the effect of the mooring position runs spread1d and spread2a are considered. The results for each type of mooring are presented as five graphs:

a) Horizontal Displacement,
b) Vertical Displacement,
c) Mooring Forces
d) Acoustic Array Position,
e) Horizontal Deviation.

The latter two graphs (d and e) should contain a family of curves, one curve for each tension considered. Only 1000, 500 and 100 N tensions have been computed and, as these curves all show similar trends, only the curves for a tension of 500 N are presented here.

In discussing the graphs of horizontal displacement alternative definitions of rotation and deviation are used. They are less precise than the original definition but are simpler and allow an appreciation of the deviation and rotation to be gleaned directly from the horizontal displacement graphs.

a) the rotation is determined from a straight line through the nodes representing the upper and lower hydrophone position of the acoustic array;
b) the median is the average horizontal displacement of the upper and lower nodes;
c) the deviation is the horizontal distance of the centre node of the acoustic array from the median, this would be zero for a 'straight' array.

Using this definition, the greater the separation of the 'top' and 'bottom' horizontal displacement curves, the greater the rotation and the greater the separation of the 'centre' curve from the median, the greater the deviation. The rotation and deviation calculated by this method are similar to, the rotation and total deviation calculated by the method described in paragraph 4.1 above.

4.2.1 Bottom Moored Array

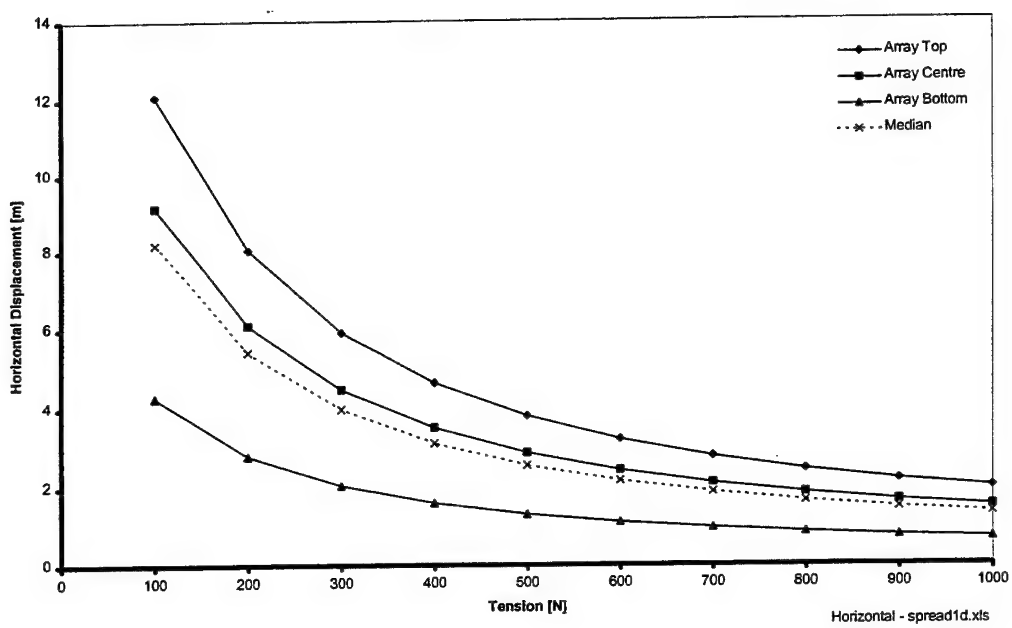

Figure 4.1 Horizontal Displacement - Bottom Moored Array

Figure 4.1 shows the variation of horizontal displacement at the top, middle and bottom of the bottom moored, acoustic array with tension. The median line is included for reference. As expected, the top of the acoustic array, which is less restrained by the bottom mooring, moves more than the bottom.

Comparing the top and bottom curves it can be seen that increasing tension decreases the separation and hence the rotation. It is significant that the reduction in this separation is not as pronounced at tensions greater than 500 N

Comparing the median and the centre curve, it can be seen that increasing tension reduces the separation and hence the deviation. Again, it is significant that this deviation is sensibly constant at tensions greater than 300 N.

The form of these curves indicates that there is an economic limit to the tension applied in terms of both array rotation and deviation. In this instance increasing the tension beyond 300 N is uneconomic and would result in a bulky, expensive and hard to handle system.

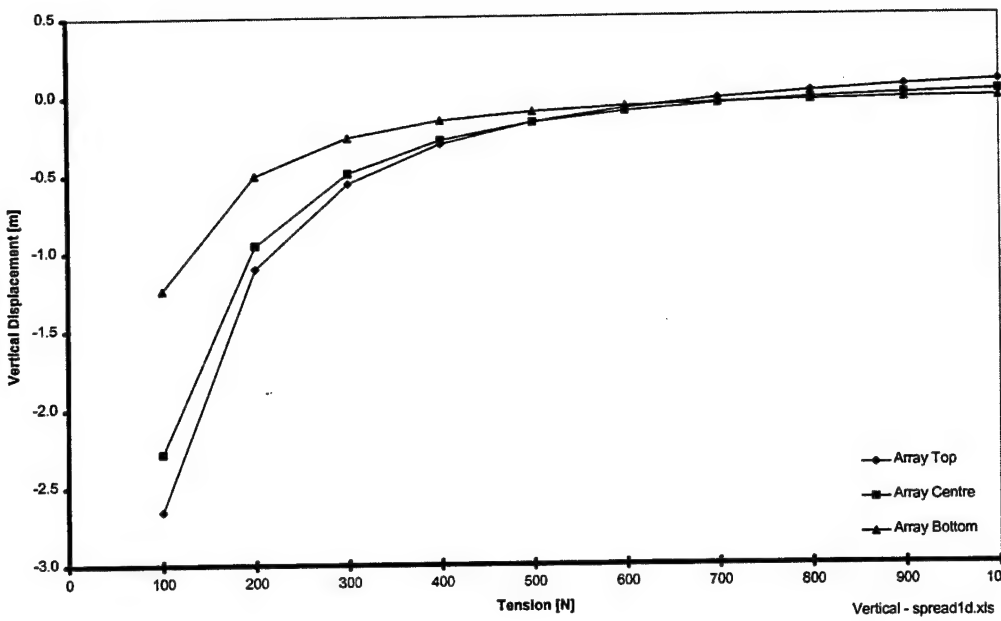

Figure 4.2 Vertical Displacement - Bottom Moored Array

Figure 4.2 shows the variation with tension of vertical displacement of the top, centre and bottom of the acoustic array. The vertical displacement is relatively small compared with the horizontal displacement. The major component of this displacement is caused by the inclination of the VLA away from the vertical, thus, as the tension is increased the angle is reduced and the array moves towards the surface. The small positive displacement at the higher tensions is caused by stretch of the array components.

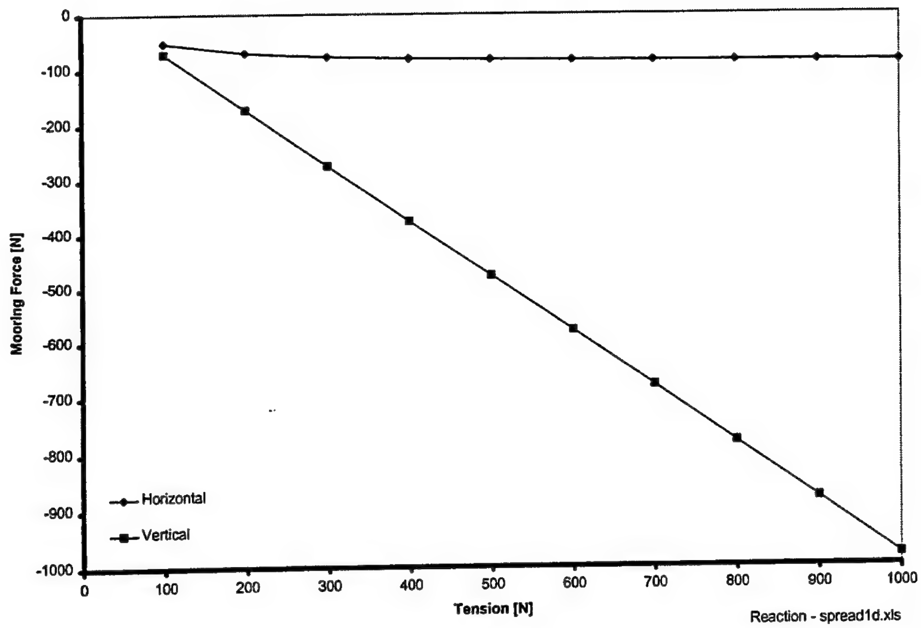

Figure 4.3 Mooring Forces - Bottom Moored Array

Figure 4.3 shows the variation of the horizontal and vertical components of the mooring load with tension. As expected, the vertical component closely follows the tension applied to the float. The horizontal component, due mainly to the crossflow drag, is substantially constant except at very small tensions when it reduces due the effect of increasing array rotation.

Figure 4.4 shows the original and deflected position of the acoustic array nodes due to the current flow when subjected to a tension of 500 N. Also shown are the 'best fit' straight line and its rotation from the vertical.

Figure 4.5 shows the horizontal position error of the nodes from the best fit, straight line. The maximum negative error occurs at the top of the acoustic array. The maximum positive error occurs near the centre of the acoustic array.

4.2.2 Surface Moored Array

Figure 4.6 shows the horizontal displacement at the top, centre and bottom of the surface moored, acoustic array. The curves are similar in shape to the bottom moored array except, as expected, the bottom of the acoustic array moves more than the top which is restrained by the surface mooring.

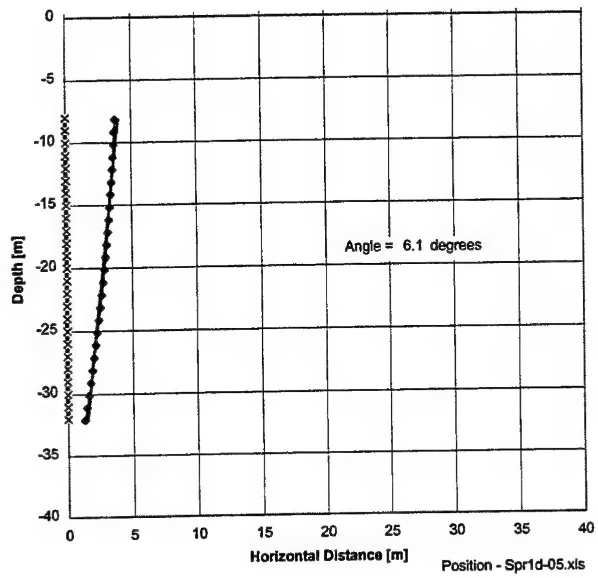

Figure 4.4 Acoustic Array Position, 500 N Tension - Bottom Moored array

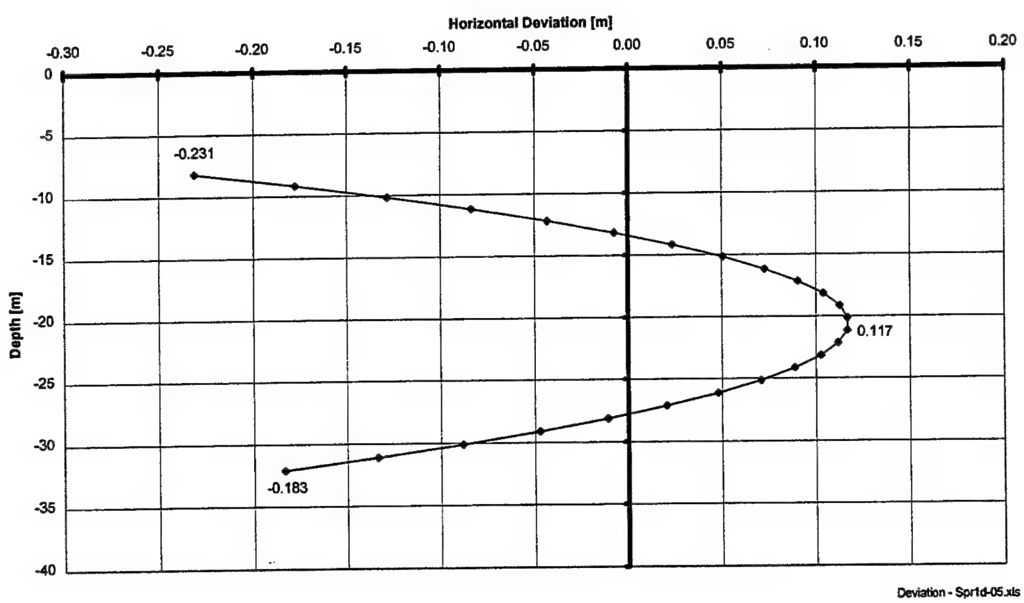

Figure 4.5 Acoustic Array Horizontal Deviation, 500 N Tension - Bottom Moored Array

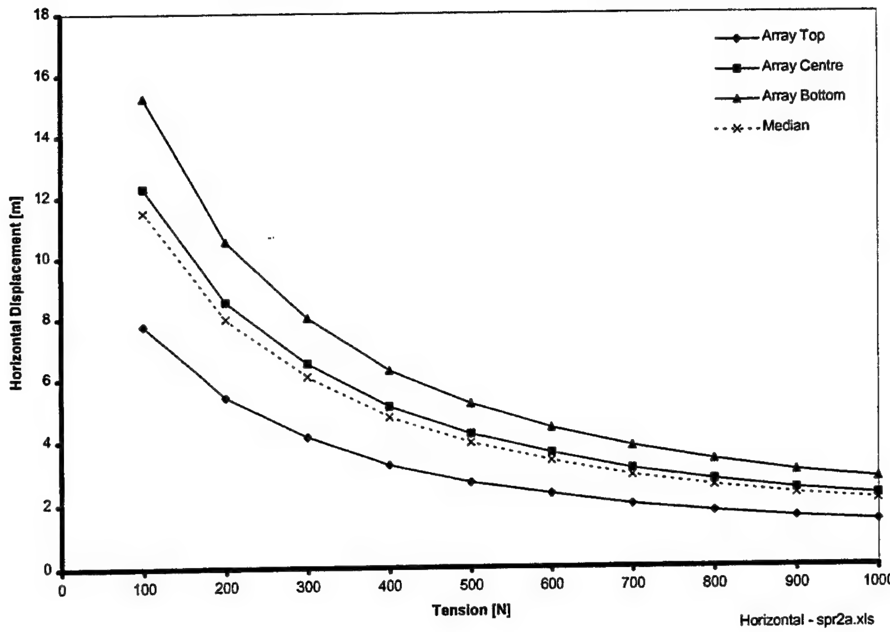

Figure 4.6 Horizontal Displacement - Surface Moored Array

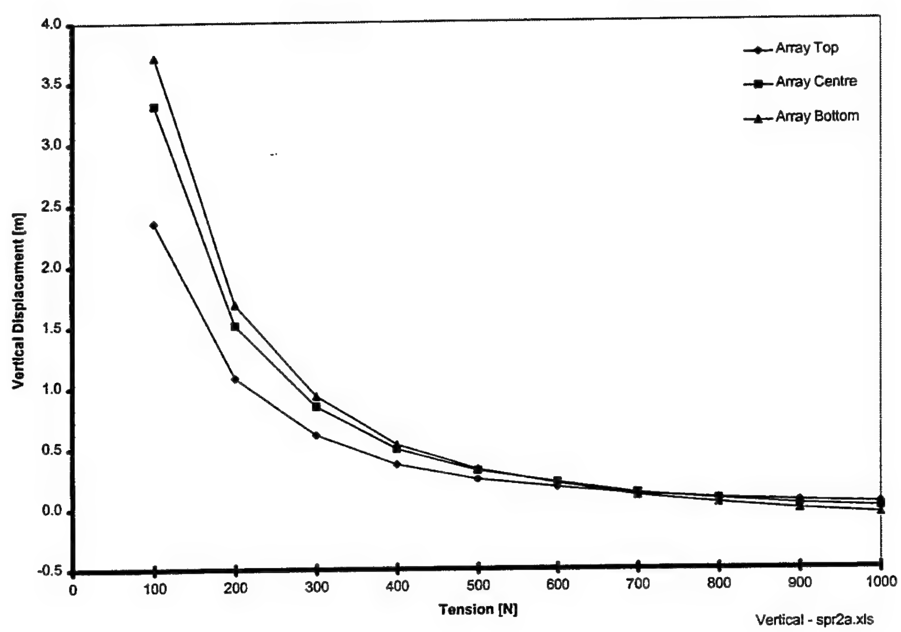

Figure 4.7 Vertical Displacement - Surface Moored array

Figure 4.7 shows the variation with tension of vertical displacement of the top, centre and bottom of the surface moored, acoustic array. As with the bottom moored array, (Figure 4.2) the vertical displacement is relatively small compared with the horizontal displacement. The major component of this displacement is caused by the inclination of the VLA away from the vertical, thus, as the tension is increased the angle is reduced and the array moves towards the bottom. The small negative displacement at the higher tensions is caused by stretch of the array components.

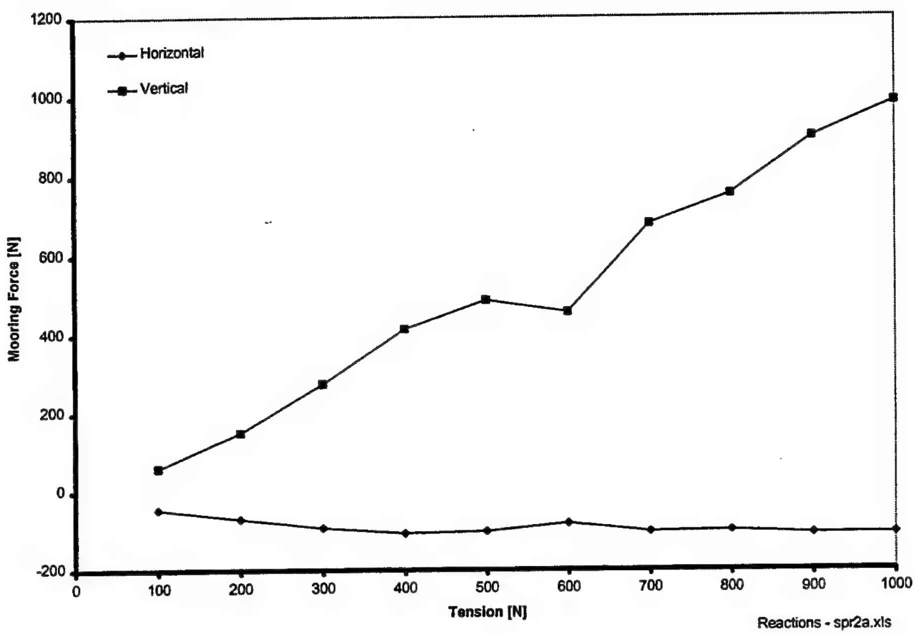

Figure 4.8 Mooring Forces - Surface Moored Array

Figure 4.8 shows the variation of the horizontal and vertical components of the mooring load with tension. As expected, the vertical component closely follows the tension applied to the float. The horizontal component, due mainly to the crossflow drag, is substantially constant except at very small tensions when it reduces due the effect of increasing array angle. The offset data points between 500 and 700 N tension appear to be caused by a glitch in the analysis program but this has not been confirmed.

Figure 4.9 shows the original and deflected position of the acoustic array nodes due to the current flow when subjected to a tension of 500 N. Also shown are the 'best fit' straight line and its rotation from the vertical.

Figure 4.10 shows the horizontal deviation of the nodes from the straight line fit. The maximum negative deviation occurs at the bottom of the acoustic array. The maximum positive deviation occurs near the centre of the acoustic array.

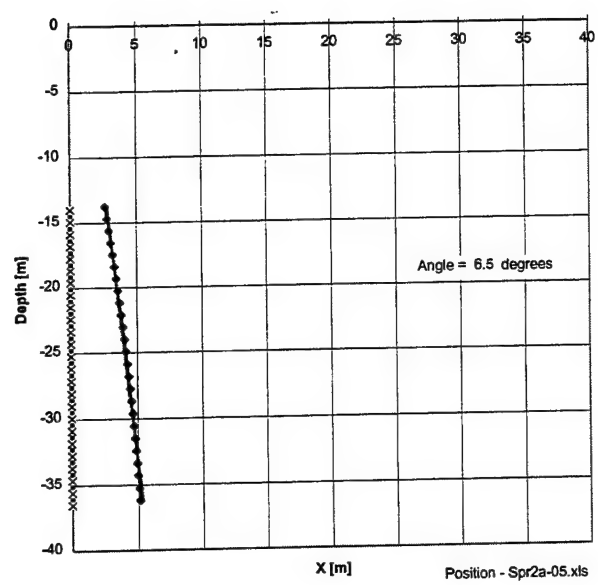

Figure 4.9 Acoustic Array Position, 500 N Tension - Surface moored Array

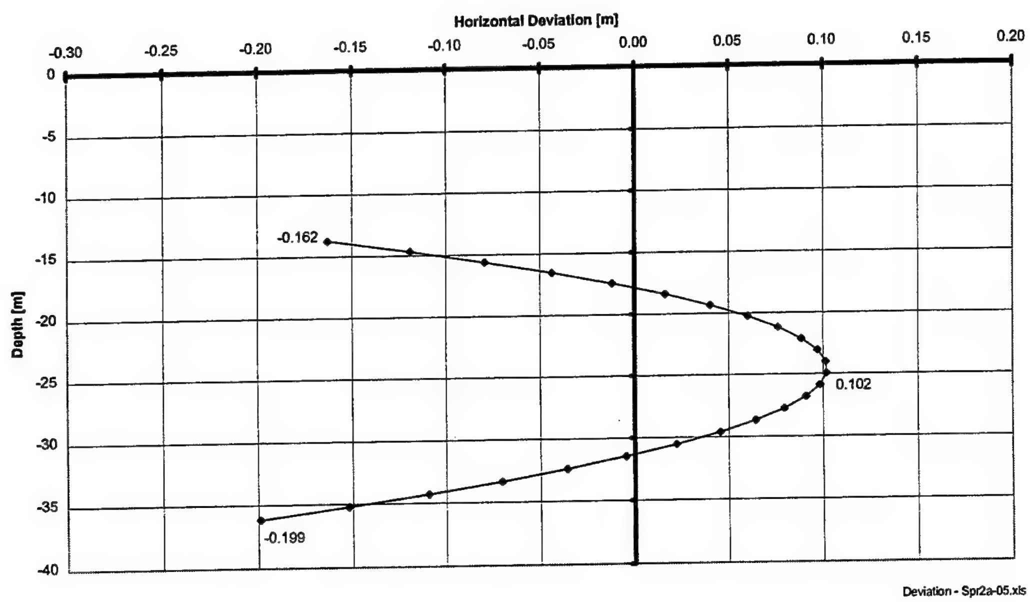

Figure 4.10 Acoustic Array Horizontal Deviation, 500 N - Surface Moored Array

4.3 Reduced Number of Strength members

An analysis was carried out with a bottom moored array with one strength member instead of two. Comparing runs spread1d and spread1f in Table 4-2, no appreciable change in the results with a single strength member, compared with the two strength member analysis, was observed.

4.4 Current Speed

An analysis was performed, spread1i, with the bottom moored array to investigate the effects of varying the current speed from 0 to 1.0 knots. A constant tension of 500 N was applied.

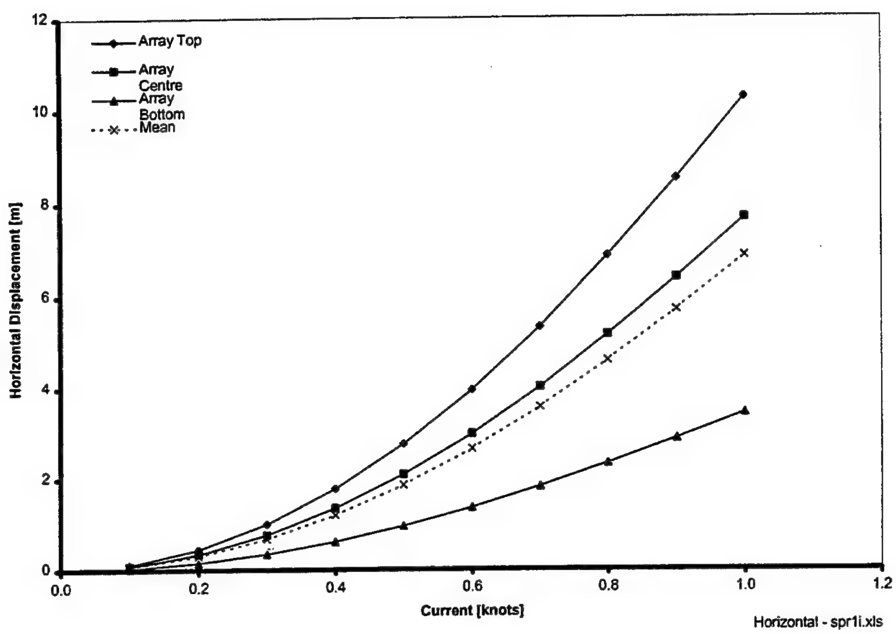

Figure 4.11 Horizontal Displacement, 500 N Tension - Bottom Moored Array

Figure 4.11 shows the horizontal displacement of the top, centre and bottom of the bottom moored, acoustic array as a function of the current. The curves almost follow the well-known square law (actually $deflection = const \times current^{1.97}$). It can also be seen that the curve for the bottom and top diverge indicating an increasing angle to the vertical, and, since the centre curve diverges from the median, the curvature also increases with current speed. Thus, for both types of mooring, it can be assumed that small increases in the current speed will cause relatively large increases in array angle and curvature.

4.5 Sea State

An analysis, spread1h, was performed to investigate the effect of the sea state on the shape of the VLA. The model used was the bottom moored array, sea state 3 (wave amplitude 1.77 m, wave period 4.6 s), a constant current profile of 0.6 knots and the applied tension was 1000 to 100 N in 100 N increments.

Figure 4.12, a reproduction of an output figure from the ANSYS software, shows the horizontal displacement with time. Table 4-4 provides a reference between the time axis and the loading condition. This figure illustrates the method used to arrive at an initial condition before varying the tension loading.

0 - 100 s	The gravity, buoyancy forces and the tension load of 1000 N is gradually applied to the VLA over a time of 100 s. This provides a steady state position of the array under 'static' loading. As this load is vertical, no horizontal deflections are produced.
100 - 200 s	The current of 0.6 knots is applied as a step input and the transient effects allowed to stabilise over the 100 s interval.
200 - 700 s	A wave train is applied to the system and the transient effects allowed to stabilise over the 500 s interval.
700 - 1600 s	The tension load is gradually reduced by 100 N every 100 s.

Table 4-4 Solution Points for Sea State Analysis

Time [s]	Tension [N]	Current [knots]	Sea State
0	0	0	0
100	1000	0	0
200	1000	0.6	0
700	1000	0.6	3
800	900	0.6	3
900	800	0.6	3
1000	700	0.6	3
1100	600	0.6	3
1200	500	0.6	3
1300	400	0.6	3
1400	300	0.6	3
1500	200	0.6	3
1600	100	0.6	3

It can be seen from Figure 4.12 that the introduction of the Sea State 3 causes an increased displacement with some increase in rotation and divergence. When the reduction in tension is commenced at 800 s, both the rotation and the divergence increase with time (decreasing tension). Thus, an increase in Sea State will result in greater angles and divergence than those at sea state zero.

The jitter in the curves is the result of the wave action and is basically at the frequency of the wave.

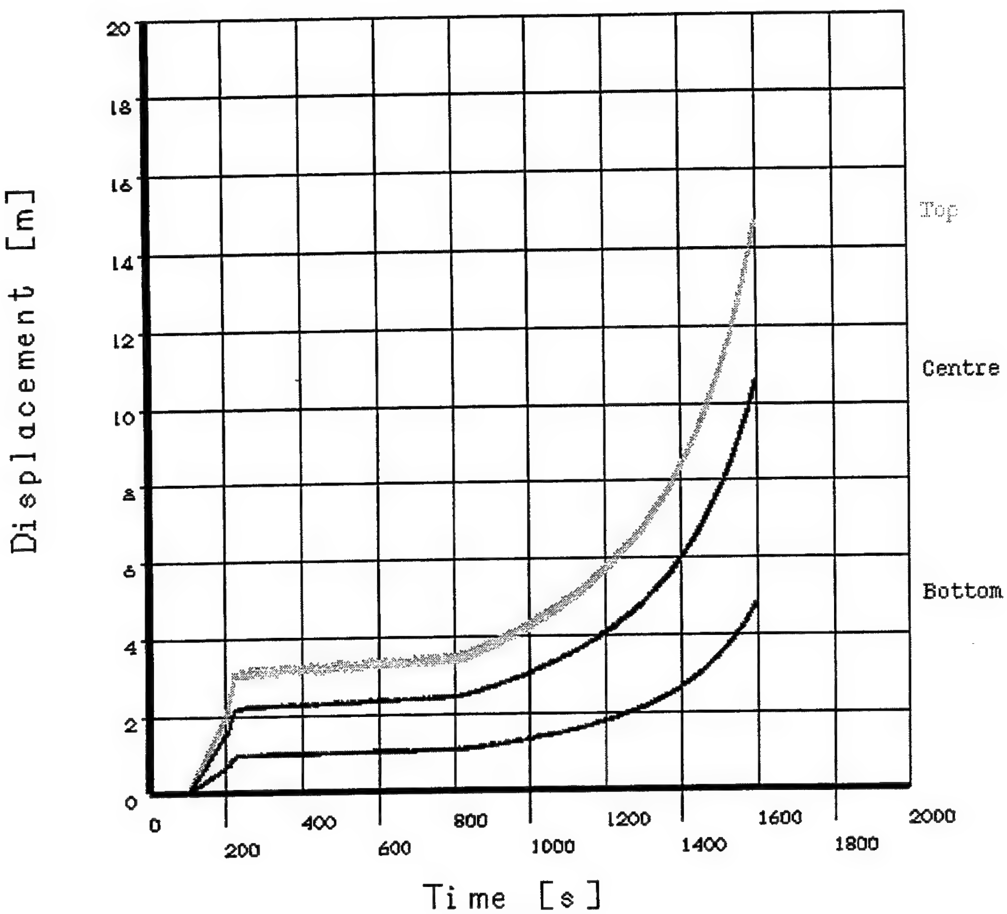

Figure 4.12 Horizontal Displacement, Sea State 3, Current 0.6 knot - Bottom Moored Array

5. Conclusions

Applying tension to limit the deflection of the acoustic section of a VLA caused by current flow is not an effective method to employ particularly when the required deflections are small.

Applying tension to the array is more effective in limiting the lateral displacement and the rotation, rather than the deviation. Referring to the arrays of this report, we conclude that 500 to 600 N is the practical limit for restricting the lateral displacement and rotation whereas 300 to 400 N can be considered the limit for restricting the deviation (Figure 4.1 and Figure 4.6).

These analyses have also shown:

a) there is little difference in the rotation or deviation between bottom or surface moored VLAs;
b) for a given tension, increasing the stress in the strength member(s) has no effect on the angle or deviation;
c) assuming a fixed maximum current speed, a constant current profile will always cause larger deflections than a shaped profile;
d) the relationship between deflection of the array and current speed is approximately a square law; and
e) increasing sea state increases the displacement, rotation and deviation of the array.

Methods that should be considered for decreasing the angle and deviation of the acoustic array are to:

a) reduce the drag coefficients of all components, particularly the acoustic array;
b) reduce the diameter of the acoustic array;
c) increase the bending stiffness of the acoustic array; and
d) optimise the shape of the float or weight to reduce its drag.

References

1. ANSYS® Software Product, Release 5.3, SAS IP Inc.

Appendix A: Input for ANSYS Bottom Moored Array

A.1 Model Input File

```
! Model Designation - spread1
/TITLE,SPREAD VLA Analysis
!*
! This model is a 24 m x 40 mm dia Vertical Line Array
! suspended in 40 m of water in currents up to 0.6 knots.
! The Tension on the VLA is controlled by an applied force at the float.
!*
! Treats the tube of the array as a cable.
!*
KEYW,PR_SET,1
KEYW,PR_STRUC,1
/PMETH,OFF
/PREP7
!*
!*
! Set Parameters
  rhow = 1025                       ! Water Density 1025 kg/cu m
  depth = 40                        ! Water Depth 40 m
!*
!*
! Cable Elements
ET,1,PIPE59                         ! Mooring Cable
  KEYOPT,1,1,1                      ! Cable option
  KEYOPT,1,6,2                      ! Print member F and M in elem coords
  R,1,0.008, ,1.2                   ! 8 mm Cable, Cd=1.2
    RMORE, , , ,0.01                ! Ct=0.01
  UIMP,1,EX  , , ,5.33e10,
  UIMP,1,DENS, , ,5385,
  UIMP,1,ALPX, , ,1.51e-05,
  UIMP,1,NUXY, , ,0.29
  TB,WATER,1
    TBMODIF,1,3,depth               ! Water Depth
    TBMODIF,1,4,rhow                ! Water Density
!*
ET,4,PIPE59                         ! Float Cable
  KEYOPT,4,1,1                      ! Cable option
  KEYOPT,4,6,2                      ! Print member F and M in elem coords
  R,4,0.0127, ,1.2                  ! 12.7 mm Cable, Cd=1.2
  RMORE, , , ,0.01                  ! Ct=0.01
  UIMP,4,EX  , , ,20e9
  UIMP,4,DENS, , ,763
  UIMP,4,ALPX, , ,1.51e-05
  UIMP,4,NUXY, , ,0.29
  TBCOPY,WATER,1,4
!*
! VLA Elements
ET,3,LINK10                         ! Strength Member
  KEYOPT,3,2,2                      ! Small Stiffnesses assigned
  KEYOPT,3,3,0                      ! Tension Only (Cable) Option
  R,3,4.28e-6                       ! Effective Area 4.28e-6 sq m
  UIMP,3,EX  , , ,20e9
  UIMP,3,DENS, , ,1067,
  UIMP,3,ALPX, , ,1.51e-05,
  UIMP,3,NUXY, , ,0.33
!
```

```
ET,2,PIPE59                              ! Tube
  KEYOPT,2,1,1                           ! Cable option
  KEYOPT,2,6,2                           ! Print member F and M in elem coords
  R,2,0.04,0.003,1.2                     ! 40 mm x 3 mm Wall Tube, Cd=1.2
    RMORE,0.8186, , ,0.01                ! Internals 0.8186 kg/m, Ct=0.01
  UIMP,2,EX  , , ,18.4e6,
  UIMP,2,DENS, , ,1320,
  UIMP,2,ALPX, , ,1.51e-05,
  UIMP,2,NUXY, , ,0.33
  TBCOPY,WATER,1,2
!*
! Float Elements
ET,5,PIPE59
  R,5,0.4, ,1.2                          ! Float
  RMORE, , , ,0.1                        ! Ct=0.01
  UIMP,5,EX  , , ,68.26e9
  UIMP,5,DENS, , ,rhow
  UIMP,5,ALPX, , ,1.51e-05,
  UIMP,5,NUXY, , ,.33
  TBCOPY,WATER,1,5
!*
! Define Nodes
   N,1,0,0,-40                           ! Anchor
   N,9,0,0,-32                           ! Bottom of Array
      Fill,1,9
   N,33,0,0,-8                           ! Top of Array
      Fill,9,33
   N,37,0,0,-4                           ! Bottom of Float
      Fill,33,37
   N,38,0,0,-3                           ! Top of Float
!*
!  Define Elements
   ! Mooring Cable
      TYPE,1,
      MAT,1,
      REAL,1,
        E,1,2
        EGEN,8,1,-1
!*
   ! VLA
      TYPE,2                             ! Tube
      MAT,2
      REAL,2,
        E,9,10
      TYPE,3
      MAT,3
      REAL,3
        E,9,10                           ! Strength Member #1
        E,9,10                           ! Strength Member #2
          EGEN,24,1,-3
!*
  ! Float Cable
      TYPE,4
      MAT,4
      REAL,4
        E,33,34
          EGEN,4,1,-1
!*
  ! Float
      TYPE,5
      MAT,5
      REAL,5
        E,37,38
!*
!*
Pressure=101.3E3                         ! Atmospheric Pressure [PA]
ESEL,S,MAT, ,2                           ! Select Array Elements Material 2
CM,ARRAY,ELEM                            ! Form element component ARRAY
SFE,ALL,1,PRES, ,Pressure*4              ! Apply Internal Pressure To ARRAY Elements
```

```
ESEL,all                    ! Reselect all elements
! Apply Constraints
D,ALL,   UY,0               ! Fix all nodes in UY
D,  1,   UX,0, ,   , ,UZ    ! Fix anchor node 1 in UX and UZ
!*
! Load with Gravity
ACEL,0,0,9.81
!*
!*
/DSCALE,1,1                ! Deflection Scaling - True Geometry
/VIEW,1, ,-1
/PNUM,NODE,1
/NUMBER,0
/PBC,   U, ,1
/PBC, ROT, ,1
/PBC,ACEL, ,1
EPLO
SAVE
!*
```

A.2 Solution Input File

```
! spread.sol04
/SOLU
! Model Designation spread1
! Parameters
   tension=1000
   dtime=100
   current=0
!*
ANTYPE,4
TRNOPT,FULL
LUMPM,0
EQSLV,FRONT,1e-08,0
AUTOTS,OFF
NLGEOM,ON
SSTIF,ON
NROPT,AUTO
TIMINT,OFF                          ! Transient Effects OFF
KBC,0                               ! Ramped Loads
!*
OUTPR,BASIC,LAST
OUTRES,ALL,ALL
!*
TIME,dtime
NSUBST,1
NCNV,2
F,38,FZ,tension                     ! Apply Tension to top of cable
/TITLE,SPREAD VLA Analysis - Tension %tension% N, Current %current% knots
SOLVE                               ! Solve Loadstep #1
!*
!*
current = 0.6                       ! 0.6 knots
!*
TB,WATER,1                          ! For Mooring Cable
   TBMODIF,2,1,-depth
   TBMODIF,2,2,current*0.5144
TBCOPY,WATER,1,2                    ! For Tube
TBCOPY,WATER,1,4                    ! For Float Cable
TBCOPY,WATER,1,5                    ! For Float
!*
AUTOTS,ON
LNSRCH,ON
PRED,ON, ,ON
TIMINT,ON,STRUC                     ! Turn ON Structural Inertia Effects
DELTIM,0.01,0,0,0                   ! Minimum Timestep 0.01 s
NEQIT,100                           ! Maximum of 100 Equilibrium Operations
OUTRES,ALL,LAST                     ! Results at end of Loadstep
CNVTOL,F, ,0.01,2,1                 ! TOLER = 1%, MINREF = 1 N
!*
*DO,I,1,10,1
  dtime=dtime+100                   ! Increment time
  F,38,FZ,tension                   ! Apply tension
  TIME,dtime
  /TITLE,SPREAD VLA Analysis - Tension %tension% N, Current %current% knots
  SOLVE                             ! Solve Loadstep
  tension=tension-100               ! Decrement tension
*ENDDO
FINISH
```

Appendix B: Input for ANSYS Surface Moored Array

B.1 Model Input File

```
! Model Designation - spread2 model.01
/TITLE,Suspended VLA Analysis
!*
! This model is a Vertical Line Array of 25 Hydrophones (980 mm spacing)
! Tube - 28.5 m Long x 40 mm dia
! Suspended in 40 m of water
! Currents up to 0.6 knots.
! The Tension on the VLA is controlled by an applied force at the Weight.
! The tube of the array is treated as a cable.
!*
KEYW,PR_SET,1
KEYW,PR_STRUC,1
/PMETH,OFF
/PREP7
!*
!*
! Set Parameters
  rhow = 1025                       ! Water Density 1025 kg/cu m
  depth = 40                        ! Water Depth 40 m
!*
ET,1,PIPE59                         ! Mooring Rope
  KEYOPT,1,1,1                      ! Cable option
  KEYOPT,1,6,2                      ! Print member F and M in elem coords
  R,1,0.0127, ,1.2                  ! 12.7 mm Cable, Cd=1.2
  RMORE, , , ,0.01                  ! Ct=0.01
  UIMP,1,EX  , , ,20e9
  UIMP,1,DENS, , ,763
  UIMP,1,ALPX, , ,1.51e-05
  UIMP,1,NUXY, , ,0.29
  TB,WATER,1
    TBMODIF,1,3,depth               ! Water Depth
    TBMODIF,1,4,rhow                ! Water Density
!*
! VLA Elements
ET,2,LINK10                         ! Strength Member
  KEYOPT,2,2,2                      ! Small Stiffnesses assigned
  KEYOPT,2,3,0                      ! Tension Only (Cable) Option
  R,2,4.28e-6                       ! Effective Area 4.28e-6 sq m
  UIMP,2,EX  , , ,20e9
  UIMP,2,DENS, , ,1067,
  UIMP,2,ALPX, , ,1.51e-05,
  UIMP,2,NUXY, , ,0.33
!
ET,3,PIPE59                         ! Tube
  KEYOPT,3,1,1                      ! Cable option
  KEYOPT,3,6,2                      ! Print member F and M in elem coords
  R,3,0.04,0.003,1.2                ! 40 mm x 3 mm Wall Tube, Cd=1.2
    RMORE,0.8186, , ,0.01           ! Internals 0.8186 kg/m, Ct=0.01
  UIMP,3,EX  , , ,18.4e6,
  UIMP,3,DENS, , ,1320,
  UIMP,3,ALPX, , ,1.51e-05,
  UIMP,3,NUXY, , ,0.33
  TBCOPY,WATER,1,3
!*
! Can Elements
```

```
ET,4,PIPE59
  R,4,0.22, ,1.2                    ! Can 500 mm x 22 mm dia
  RMORE, , , ,0.1                   ! Ct=0.01
  UIMP,4,EX   , , ,68.26e9
  UIMP,4,DENS, , ,rhow
  UIMP,4,ALPX, , ,1.51e-05,
  UIMP,4,NUXY, , ,.33
  TBCOPY,WATER,1,4
!*
! Weight Elements
ET,5,PIPE59
  R,5,0.5, ,1.2                     ! Weight 1 m x 220 mm dia
  RMORE, , , ,0.1                   ! Ct=0.01
  UIMP,5,EX   , , ,68.26e9
  UIMP,5,DENS, , ,rhow
  UIMP,5,ALPX, , ,1.51e-05,
  UIMP,5,NUXY, , ,.33
  TBCOPY,WATER,1,5
!*
! Define Nodes
   N,101,0,0,  0                    ! Surface Anchor
   N,110,0,0, -9                    ! Top of Can
      Fill,101,110
   N,111,0,0, -9.5                  ! Bottom of Can
   N,115,0,0,-13                    ! D2
      FILL,111,115
   N,  1,0,0,-14                    ! H1
   N, 25,0,0,-36.5                  ! H25
      Fill,1,25                     ! H2 to H24
   N,201,0,0,-37                    ! D2
   N,202,0,0,-38                    ! Top of Weight
   N,203,0,0,-39                    ! Bottom of Weight
!*
!  Define Elements
   ! Mooring Rope
      TYPE,1,
      MAT,1,
      REAL,1,
        E,101,102
        EGEN,9,1,-1
   ! Can
      TYPE,4
      MAT,4
      REAL,4
        E,110,111
!*
   ! Upper VLA - Can to D1
      TYPE,3                        ! Tube
      MAT,3
      REAL,3,
        E,111,112
      TYPE,2
      MAT,2
      REAL,2
        E,111,112                   ! Strength Member #1
        E,111,112                   ! Strength Member #2
          EGEN,4,1,-3
!*
  ! Upper VLA - D1 to H1
      TYPE,3                        ! Tube
      MAT,3
      REAL,3,
        E,115,1
      TYPE,2
      MAT,2
      REAL,2
        E,115,1                     ! Strength Member #1
        E,115,1                     ! Strength Member #2
!*
```

```
 ! Hydrophone Section - H1 to H25
     TYPE,3                         ! Tube
     MAT,3
     REAL,3,
       E,1,2
     TYPE,2
     MAT,2
     REAL,2
       E,1,2                        ! Strength Member #1
       E,1,2                        ! Strength Member #2
         EGEN,24,1,-3
!*
 ! Lower VLA - H25 to D2
     TYPE,3                         ! Tube
     MAT,3
     REAL,3,
       E,25,201
     TYPE,2
     MAT,2
     REAL,2
       E,25,201                     ! Strength Member #1
       E,25,201                     ! Strength Member #2
!*
 ! Lower VLA - D2 to Weight
     TYPE,3                         ! Tube
     MAT,3
     REAL,3,
       E,201,202
     TYPE,2
     MAT,2
     REAL,2
       E,201,202                     ! Strength Member #1
       E,201,202                     ! Strength Member #2
!*
  ! Weight
     TYPE,5
     MAT,5
     REAL,5
       E,202,203
!*
!*
Pressure=101.3E3                     ! Atmospheric Pressure [PA]
ESEL,S,MAT, ,3                       ! Select Array Elements Material 2
CM,TUBE,ELEM                         ! Form element component TUBE
SFE,ALL,1,PRES, ,Pressure*4          ! Apply Internal Pressure To TUBE Elements
ESEL,all                             ! Reselect all elements
! Apply Constraints
D,ALL,  UY,0                         ! Fix all nodes in UY
D,101,  UX,0, ,  , ,UZ               ! Fix anchor node 101 in UX and UZ
!*
! Load with Gravity
ACEL,0,0,9.81
!*
!*
/DSCALE,1,1                          ! Deflection Scaling - True Geometry
/VIEW,1, ,-1
/PNUM,NODE,1
/NUMBER,0
/PBC,   U, ,1
/PBC, ROT, ,1
/PBC,ACEL, ,1
EPLO
SAVE
!*
```

B.2 Solution Input File

```
! spread2.sol01
/SOLU
! Model Designation spread1
! Parameters
   tension=1000
   dtime=100
   current=0
!*
ANTYPE,4
TRNOPT,FULL
LUMPM,0
EQSLV,FRONT,1e-08,0
AUTOTS,OFF
NLGEOM,ON
SSTIF,ON
NROPT,AUTO
TIMINT,OFF                          ! Transient Effects OFF
KBC,0                               ! Ramped Loads
!*
OUTPR,BASIC,LAST
OUTRES,ALL,ALL
!*
TIME,dtime
NSUBST,1
NCNV,2
F,203,FZ,-tension                   ! Apply Tension to weight
/TITLE,Suspended VLA Analysis - SS 0, %tension% N, %current% knots
SOLVE                               ! Solve Loadstep #1
!*
!*
current = 0.6                       ! 0.6 knots
!*
TB,WATER,1                          ! For Mooring Rope
   TBMODIF,2,1,-depth
   TBMODIF,2,2,current*0.5144
TBCOPY,WATER,1,3                    ! For Tube
TBCOPY,WATER,1,4                    ! For Can
TBCOPY,WATER,1,5                    ! For Weight
!*
AUTOTS,ON
LNSRCH,ON
PRED,ON, ,ON
TIMINT,ON,STRUC                     ! Turn ON Structural Inertia Effects
DELTIM,0.005,0,0,0                  ! Minimum Timestep 0.005 s
NEQIT,100                           ! Maximum of 100 Equilibrium Operations
OUTRES,ALL,LAST                     ! Results at end of Loadstep
CNVTOL,F, ,0.01,2,1                 ! TOLER = 1%, MINREF = 1 N
!*
*DO,I,1,10,1
  dtime=dtime+100                   ! Increment time
  F,203,FZ,-tension                 ! Apply tension
  TIME,dtime
  /TITLE,Suspended VLA Analysis - SS 0, %tension% N, %current% knots
  SOLVE                             ! Solve Loadstep
  tension=tension-100               ! Decrement tension
*ENDDO
FINISH
```

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19. ABSTRACT

As Vertical Line Arrays (VLA) are used at increasingly higher frequencies (3 kHz), the importance of the straightness of the array increases. Finite Element Analysis (FEA) has been used to estimate the shape of typical VLAs subject to currents in shallow water. Two typical VLA configurations have been modelled and the results presented.